DOCUMENT RESUME

ED 347 176 TM 018 561

AUTHOR Fisher, Mark A.
TITLE Categorization, or Schema Selection in Graph Comprehension.
PUB DATE Apr 92
NOTE 16p.; Paper presented at the Annual Meeting of the American Educational Research Association (San Francisco, CA, April 20-24, 1992).
PUB TYPE Reports - Research/Technical (143) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS Analysis of Variance; *Classification; Cluster Analysis; *College Students; Comparative Analysis; *Comprehension; *Data Interpretation; *Graphs; Higher Education; Mathematics Achievement; Memory; Multidimensional Scaling; *Schemata (Cognition); Visual Perception
IDENTIFIERS Graphic Representation

ABSTRACT

A model of graph comprehension is proposed including perceptual and memory processes. Multidimensional scaling (MDS), cluster analysis, and analysis of variance (ANOVA) were used to determine how college students with different mathematical experience read different types of bar graphs. Data were collected at the University of Oklahoma (Norman) during the summer 1991 semester from the following subjects: 28 students (mostly freshmen) in an intermediate algebra course; 39 students (mainly sophomores) in a Calculus II course; and 28 seniors and graduate students in an upper division calculus-based applied statistics course. The MDS and cluster analysis showed that there were differences in how the different groups of subjects clustered the different bar graph types. Of four bar graph types and two orientations, the graph types clustered together were simple and grouped (side by side) bar graphs. Using ANOVA, it was found that these graph types were read equally well and were read more accurately than were the other graph types. This finding indicates that graphs of different types and levels of perceptual complexity may share a single mental model or schema for graph reading. Subjects with more mathematical experience used graph orientation to a greater degree in their typicality ratings than did subjects with less mathematical experience, and it appeared that they may have had better strategies for recognizing the trends displayed in graphs. Seven figures and 1 table illustrate the study, and there is a 27-item list of references. (Author/SLD)

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Categorization, or Schema Selection in Graph Comprehension

A Paper Presented at the Annual Meeting of the American Educational Research Association
San Francisco, CA, April 1992

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Mark A. Fisher, Phillips University, Enid, OK 73701

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Abstract: A model of graph comprehension is proposed including perceptual and memory processes. Multidimensional scaling, cluster analysis and analysis of variance were used to determine how college students with different mathematical experience read different types of bar graphs. The MDS and cluster analysis showed there were differences in how the different groups of subjects clustered the different bar graph types. Of four bar graph types and two orientations the graph types clustered together were simple and grouped (side by side) bar graphs. Using ANOVA it was found that these graph types were read equally well and were read more accurately than the other graph types. This indicates that graphs of different types and levels of perceptual complexity may share a single mental model or schema for graph reading.

Introduction

The use of graphs to convey quantitative information has become very commonplace. So commonplace that quantitative graphics are often taken for granted. Graphs are able to communicate information that would be difficult to communicate in any other way, in particular, trends and comparisons. However, many who construct graphs do not take into account the level of graphical literacy of their audience, assuming that the visual nature of the graph will make the communication automatic. Individuals that are highly skilled in reading graphs sometimes seem to have difficulty recalling that graphs can present a challenge to a reader unfamiliar with the graph type presented. Like all forms of reading, graph reading is a learned process of comprehension. It was noted by Vernon (1946) that

> It is not often sufficiently recognized by those who advocate visual methods of presentation that the graph and the chart are no more immediately representational and no less symbolic of the information they are intended to convey than are verbal and mathematical statements. But whereas nearly everyone in the course of their upbringing acquires some facility making verbal statements of ideas and meanings, only the specially educated learn to interpret factual information from graphs and charts.

Thus graph comprehension is a reading task, with similarities to other reading tasks. Reading is cognitive processing of visually presented information. This involves incorporating the information into *existing* text schema or models used for comprehension.

Much of the research in the nature of the graph comprehension process has been performed with an emphasis on the visual nature of graphs. *Graphical perception* studies have provided insights into how different types of perceptual objects (bars, lines, circles,

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angles, etc.) communicate quantity (see, Cleveland, 1985, 1991; Spence, 1990; Spence and Lewandowsky, 1991). While graphical perception is clearly important for a complete understanding of this highly visual medium of communication, the memory and cognitive processes involved in the comprehension of graphs have not been as widely studied. The study reported here is intended as a step in the process of understanding the *memory processes* used in graph comprehension. In particular this study was designed to learn more about the *graph categorization*, or schema selection process and how it affects the graph comprehension process.

Framework

The Model of Graph Comprehension. The model of graph comprehension used in this study is based on the graph schema theory of Pinker (1991) and the memory process theories of Kosslyn (1985, 1989). These models are adapted and combined in Figure 1. The major processes involved in this model are:

(1) *attending*, when the graphical stimulus is first seen and attended to, a graph icon is created in a sensory register;
(2) *categorizing*, the graph icon in the sensory register is matched to an appropriate graph schema or mental model of the graph stimulus type and problem scenario stored in long-term memory;
(3) activating the appropriate schema, the model accessed during categorization is place in working memory; and
(4) integration, consisting of more directed calls for perceptual processes guided by the strategies contained in the selected schema of mental model, these processes fit the information in the graphical stimulus into the model and determine answers to the problem stimulus.

These processes are not necessarily presented in a pure sequence of occurrence. For example, after initial attending if a particular graphical stimulus fails to integrate with the chosen schema, more attending will occur and the stimulus can be recategorized. In addition the importance of the problem context is emphasized in the model, since it has been found that the context of a graphical stimulus can affect how a graph is read (McKnight, Kallman, and Fisher, 1990).

There are two principle types of processes in this model. First there are the perceptual processes of attending and integration. Studies that examine these perceptual processes have been performed in psychological and statistical contexts under the title of graphical perception. The other major type of process emphasized in this model consists of the

memory processes of categorization and activation. Some research has been conducted concerning the memory processes for graphs. These studies tend to indicate that graph schema, or mental models for comprehending graphical information, do exist.

Marshall (1976) found that when subjects read a passage about sonnets and a passage about graphs, the subjects were better able to recall information from the text concerning graphs. It was hypothesized that the subjects had more familiarity with graphs therefore were better able to understand the passage about graphs. This may indicate that there is an organized mental model for graphs while a less organized model was available for the less familiar sonnets.

Simcox (1983a, 1983b) also looked at some aspects of memory processes for graphs. For example how information in a graphical display is "chunked" or summarized, minimizing the amount of human memory required for the display. Also, in considering atypical tasks using graphs, it was found that it took more time to answer atypical questions than questions that were typical of a graphical display type. Both summarization and expected question types are features that graph schema should possess.

If graph schema are used to organize the graph comprehension process then there should be a dependence on an individual's prior knowledge of a graph type in this processing. In an examination of this Curcio (1987) examined how an individual's prior knowledge of a graph type affected how well that individual was able to read that graph type. It was found that knowledge of graph type was correlated to reading skill for fourth grade students but not for seventh grade students. Thus between fourth and seventh grades students have acquired the ability to read graph types that are at least somewhat unfamiliar, this may indicate generalized graph schema has been generated.

Another property of graph schema is that the schema should contain the individual's expectations of the nature of graph type. Tversky and Schiano (1989) found evidence this aspect of graph schema exists. In examination of subject drawings of recalled graphs, the recalled graphs were often more symmetric than the originally presented graph. Furthermore, graphs of lines were recalled closer to the diagonal than they were. McKnight, Kallman, and Fisher (1990) also found that subjects had expectations of graphs that affected how they read graphs. Graphs that subjects saw as "incorrect" being harder for the subject to read. Thus indicating that there are certain graph tasks that are considered more typical than others.

Categorization. The study of categorization has been used in a variety of domains to understand schema in that domain of knowledge. In particular, it has been used to understand word problems in math and physics (Hinsley, Hayes and Simon, 1977; Mayer, Larkin and Kadane, 1984; Chi, Feltovich and Glaser, 1981; Schoenfeld, 1985). Thus understanding the categorization process or the process of selecting the appropriate graph schema should significantly aid in understanding the process of graph comprehension.

While there are many theories of how individuals perform the mental process of categorization (for example, see, Smith and Medin, 1981; Hoeneck, Firment, and Case, 1987; Cohen and Basu, 1987; and Medin, 1989) there are two empirical factors that all the models of categorization must address. These are the so called *prototype effects* (Rosch, 1978). These are properties have been found to hold for many mental categories. Any examination of a categorization process should consider these effects:

(1) stimuli are rated differently with respect to level of category membership
(2) subjects find it easier to answer questions about more typical members of a category than less typical members of a category.

McKnight and Fisher (1991) found that there was evidence for the first of these two prototype effects for the category of bar graphs. In that study subjects rated bar graphs on a seven point scale from very typical to very non-typical. Consistent patterns were found in clusters of graphs. Additional differences were found between levels of mathematical experience in how graphs were grouped together. Thus mathematical experience was found to be a factor in graph categorization. This could indicate differences in the structure of graph schema.

The present paper studies how the typicality of a graph type affects how well subjects are able to read that graph type. That is, whether the category of bar graphs exhibits the second prototype effect. In particular, examining whether more typical graphs are easier for subjects to read. In addition it considers the whether one type of experience (mathematical experience) contributes to the either the categorization process or the graph reading process.

Method

Subjects. This study consisted of collecting data on several subjects' views of typicality of bar graph subtypes and their ability to read the same types of graphs. The subjects were from three different levels of mathematical experience. Data was collected at the University of Oklahoma during the Summer 1991 semester from a remedial Intermediate Algebra course consisting mostly of freshmen (N = 28), Calculus II (N = 39) consisting of mainly of sophomores, and an upper division calculus based Applied Statistics course consisting of seniors and graduate students (N = 28, after removing three subjects for incorrectly completing the instruments).

Instruments. Bar graphs were chosen for this study since most individuals are somewhat familiar with that graph type. The graphs were chosen from four subtypes (examples of these types are in Figure 2):

(1) simple bar graphs with a single bar for each independent variable,

(2) grouped bar graphs with multiple bars for each independent variable,

(3) segmented bar graphs with single bars consisting of stacked bars for each independent variable, and

(4) Isotypes (MacDonald-Ross, 1977) where the bars are formed from the repeated use of a symbol such as a circle rather than a continuous bar.

Orientation of the bars was also considered, that is whether the bars were vertical or horizontal. A third factor that went into the construction of the graphs for this study was the "pattern" of the graph, that is whether the bars increased in length, decreased in length, increased then decreased in length, decreased then increased in length, or if the bars followed none of these patterns.

Two instruments were constructed, the first to measure views of typicality, the second to measure how well the subjects were able to read both values and patterns for the selected graph types. These instruments were administered by the researcher to the subjects during their normal class time. The subjects took approximately thirty minutes to complete the two instruments, and fill out the background information sheet.

The first instrument was designed to determine how the subject groups perceived the typicality of various bar graphs. In this study typicality data was collected on forty graphs constructed with one graph of each graph type (simple, grouped, segmented and Isotype) by orientation (vertical, horizontal) by pattern (increasing, decreasing, increasing then decreasing, decreasing then increasing, and a random pattern). The subjects were then asked to rate the typicality of each graph on a seven point scale from (1) very typical to (7) very non-typical.

The second instrument used by this study consisted of twenty-four additional graphs constructed in a similar fashion to the graphs used for the typicality study. There were three graphs from each type by orientation with three of the possible patterns chosen randomly for each graph. There were two questions associated with each of the twenty-four graphs. The first directed the subjects to a particular value of the independent variable and asked them to read the corresponding value of the dependent variable and select the best answer from a choice of five possible answers. The second question directed the subjects to a particular series of values (in the case of the simple and isotype graphs the whole data set, while in the case of the grouped and segmented graphs one particular set of data from a choice of three clearly labeled) and were asked to choose the most appropriate description of the pattern of the data. Their choices were: (1) increasing; (2) decreasing; (3) increasing then decreasing; (4) decreasing then increasing; and (5) none of the above patterns.

Results

Typicality. The techniques of multidimensional scaling and cluster analysis have been used with success in examining the process of categorization. In particular categorization of natural categories (for example, birds and mammals, Rips, Shoben, and Smith, 1973). These techniques have also been used to examine the categorization of word problems (for example, Veldhuis, 1990). Dissimilarities between graphs were then derived from the typicality ratings for each group of subjects. The data were then analyzed by subject groups (i.e. mathematical experience level) using multidimensional scaling (PROC ALSCAL available in the SAS library) and cluster analysis (SAS PROC CLUSTER) to produce configurations of clusters of graphs.

The configurations found using multidimensional scaling and cluster analysis are shown in Figure 3 (Intermediate Algebra), Figure 4 (Calculus II), and Figure 5 (upper division Applied Statistics). It was determined that the horizontal axis was a "typicality" dimension, while the vertical axis presented no easy interpretation. All groups of subjects rated Isotypes as least typical, segmented bar graphs more typical, with grouped bar graphs and simple bar graphs rated as most typical.

The figures show that subjects with more mathematical experience have a greater degree of separation of graphs by type and by orientation. The Intermediate Algebra students had simple and grouped bar graphs in one cluster. While the Calculus II students separated the simple and grouped bar graphs by orientation, with vertical bar graphs rated more typical than the horizontal bar graphs. The upper division Applied Statistics students continued this trend and separated the segmented bar graphs by orientation, with vertical segmented bar graphs again rated as more typical than the horizontal segmented bar graphs.

These results agreed to a large degree with a previous study (McKnight and Fisher, 1991) where students with greater mathematical experience were more likely to have paid attention to the orientation of the graph. Thus it appears that experience plays a role in the views of typicality of bar graphs. Thus the first of the two prototype effects, that is the tendency for objects in a category to have different levels of membership in the category seems to be true for the category of bar graphs.

Graph Reading Skill. The first graph reading skill question examined was to determine if there were significant differences between the three groups of subjects on these two graph reading skills. All three groups of students were able to read values from the bar graphs very well. In fact the mean totals, out of maximum 24 possible, value reading were 20.29 for Intermediate Algebra, 20.36 for Calculus II, and 20.57 for the upper division Applied Statistics. These differences were not significant ($F_{2,92} = 0.11$, $p = 0.8931$). Thus all three

groups of students were equally skilled at reading values from a variety of bar graph types. For pattern description significant differences were found ($F_{2,92} = 6.60$, $p = 0.0021$).

The next question examined was to determine if there were differences in how well different graph types and orientations were read. For value reading this created a 4 X 2, graph type by orientation design with each subject answering three questions per cell (the three graphs of a particular type and orientation). Cell means (and standard deviations) are seen in Table I (plots of these means can be seen in Figure 6). Significant differences were found for graph types ($F_{3,752} = 97.80$, $p = 0.0001$). Analysis using SAS REGWQ showed that the simple and grouped graphs were read equally well. All other differences between types were significant. These two graph types were also the most accurately read. They were followed by the Isotypes and then finally the segmented bar graphs.

Additionally there was a small, though significant ($F_{1,752} = 4.15$, $p = 0.0421$), effect for orientation, with horizontal bar graphs read slightly better than vertical bar graphs (the effect size was only 0.13 standard deviations). This result agrees with the advice in Cleveland (1985) to use horizontal graphs rather than vertical. The order of graph types for reading accuracy remained the same for both vertical and horizontal bar graphs (simple and grouped, Isotypes, then segmented).

For pattern description the design was more complicated since there were significant differences between groups of subjects in how well they were able to describe the patterns. The design was a 3 X 4 X 2, subject group by graph type by orientation with each subject providing answering three questions per graph type and orientation. Again the mathematical experience level was significant ($F_{2,736} = 18.59$, $p = 0.0001$). Of greater interest was the significant interaction between graph type and orientation ($F_{3,736} = 4.37$, $p = 0.0046$). Illustrated in Figure 7 and Table II, this interaction is apparently due to the behavior of the horizontal grouped graphs. The remaining graph types and orientations are appear much the same as for the value reading results. Horizontal grouped bar graphs seem to deviate from the previous results. This interaction makes it difficult to make comparisons between types and orientations.

Discussion

From the results of the value reading instrument it appears a subject's ability to read values from bar graphs does not depend on that mathematical experience. However, it appears that there are differences in how well different types of bar graphs are read. In addition, it appears that there is a slight difference in how bar graphs with different orientations are read.

The configurations and clusters found using the typicality data shows there are patterns to the category of bar graphs. There are differences in perceived typicality. There are also differences in how groups with different levels of mathematical experience perceive

the category of bar graphs. Therefore it seems that there is some justification in claiming that the first prototype effect, that of differential membership in a category, exists for the category of bar graphs.

Taken together the results from the typicality instrument and the value reading instrument seem to imply that the differences in the typicality rating of a graph type may be related to how well that graph type is read. Both the typicality study and the value reading study showed that *simple and grouped* graphs were somehow similar, that is they were considered to be of similar typicality and values from these graph types were read equally well. This could indicate that graph schemata may be a general models that apply to several graph types. Even if the graphs differ greatly differ in terms of perceptual complexity, they may share a single graph schema, or mental model for graph comprehension.

Thus it appears that the perceived typicality of a graph does affect how well that type of graph will be read, since graphs that were grouped together in terms of the typicality data were also read equally well. However, there is no *linear relationship* between typicality and how easy a it is to read values from a graph. One explanation for this result is that the graphs chosen for this study do not necessarily belong to the same mental category. Typicality judgments would then not be measuring the same quantity across the different categories.

One example of this might be orientation. Orientation was found to have an affect on how well a bar graph was read, horizontal bar graphs were consistently read somewhat more accurately than vertical bar graphs. However vertical bar graphs were generally considered to be the more typical. This result presents a challenge to the hypothesis that the category of graphs exhibits the second of the prototype effects, that is whether more typical members of the category are easier to answer questions about than less typical members, since there seems to be the reverse effect showing in terms of orientation.

It seems likely that most individuals would not make a categorical distinction between vertical bar graphs and horizontal bar graphs. Thus it would seem that vertical and horizontal bar graphs should belong to the same mental category. Further research should be performed to determine if this is the case. If these graph types are considered to be in the same category, another explanation is needed. One possible explanation would be to consider, not just the typicality of the graphs, but the perceptual complexity of the graphs. Since the readability of a graph is a function of both its typicality and the perceptual complexity. Cleveland (1985) suggested using horizontal bar graphs, indicating that some form of perceptual difference in horizontal and vertical bar graphs may be contributing to the differences in reading scores.

A second example of the second prototype effect not being seen is that the most typical graph types of simple bar graphs and grouped bar graphs were also the easiest to read value from, however the least typical Isotype bar graphs were more easily read than the

somewhat more typical segmented bar graphs. Isotypes, therefore present difficulties to the hypothesized model. Individuals consider Isotypes to be more readable than any bar graph type except the simple bar graphs, and researcher judgments were that they were perceptually less complex than the other bar graph types (McKnight and Fisher, 1991). However, Isotypes are not read as well as grouped bar graphs which appear to be more perceptually complex. This may indicate that Isotypes may form a different category of graphs and thus not be constrained by the same function of typicality and perceptual complexity as the other bar graphs. Another explanation is that, while Isotypes are perceptually less complex they are more complex to work with mentally, since conversion of number to the actual amount must be performed. Since Isotypes are relatively common, this should be researched further.

Thus the second prototype effect was not demonstrated by this study. However, there are clear relationships between the typicality rating of a graph type and how well subjects can read that graph type. In addition, there is evidence with higher typicality a graph *generally* is easier to read. Even if there are no differences in categories for the graphs chosen for this study, the graph comprehension model proposed is still reasonable since the model (Figure 1) puts a heavy emphasis on perceptual factors in the process of graph comprehension. Perceptual abilities play many important roles in reading values from a graph.

The study reported here has also shown that the categorization process is also important to the process of graph comprehension. One reason for this is that the schema selected to use in reading the graph contains different strategies for guiding the perceptual processes that may depend on the graph type (see Simkin and Hastie, 1987, for some hypothesized strategies). Thus graph comprehension does appear to be a function of both perceptual processes and the memory process of categorization.

Furthermore, the subjects with more mathematical experience used graph orientation to a greater degree in their typicality ratings than did the subjects with less mathematical experience. Vertical bar graphs were considered generally more typical than horizontal bar graphs demonstrating differing views of bar graph typicality. Mathematical experience level was a significant factor in how well subjects were able to describe the patterns in the graphs. Thus while mathematical experience has no significant affect on *value* reading skill, there are indications that there may be some internal modifications to the schema. In particular, in better strategies for recognizing the trends displayed in graphs.

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Figure 1

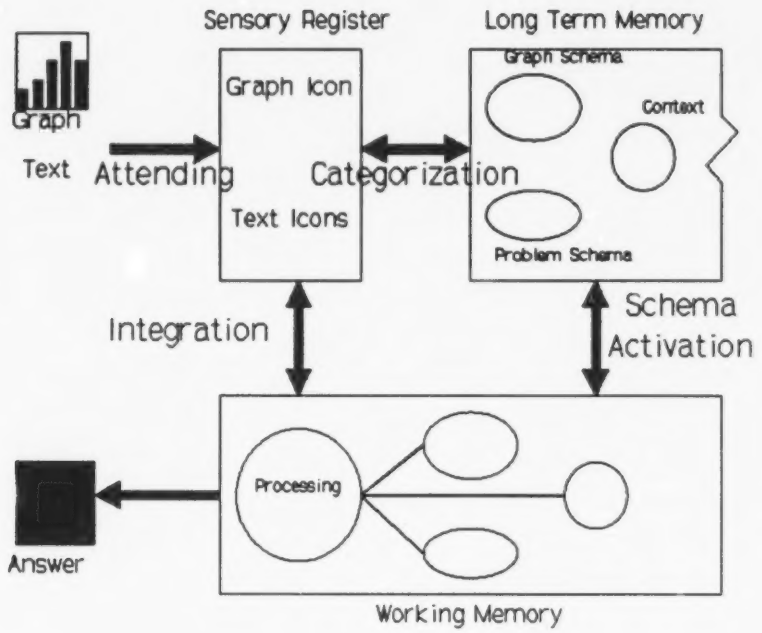
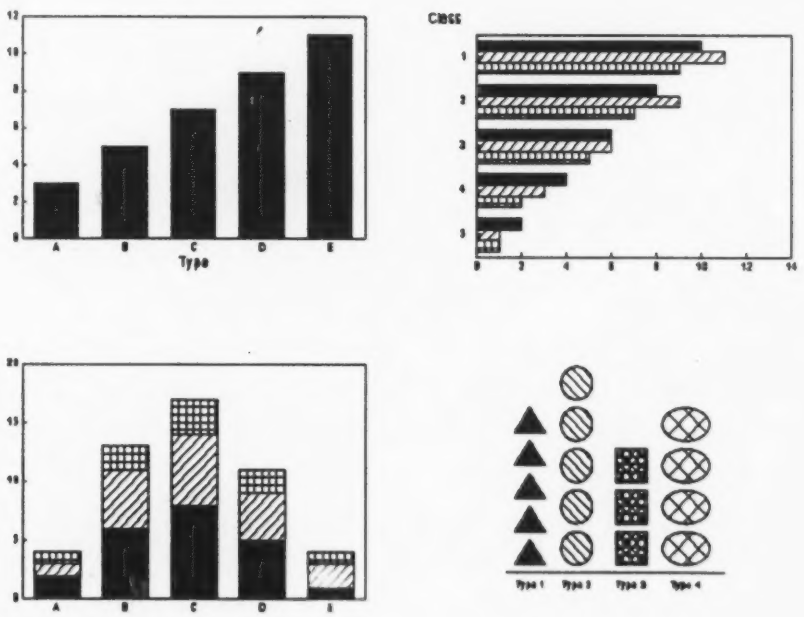


Figure 2



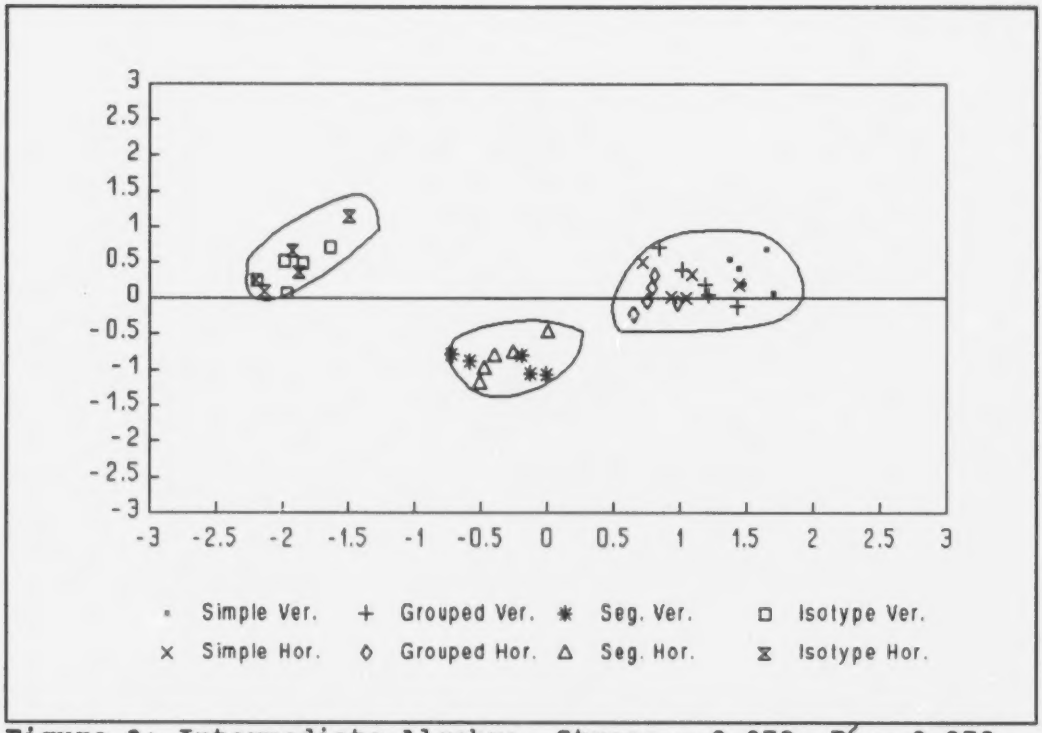


Figure 3: Intermediate Algebra. Stress = 0.079. R^2 = 0.978.

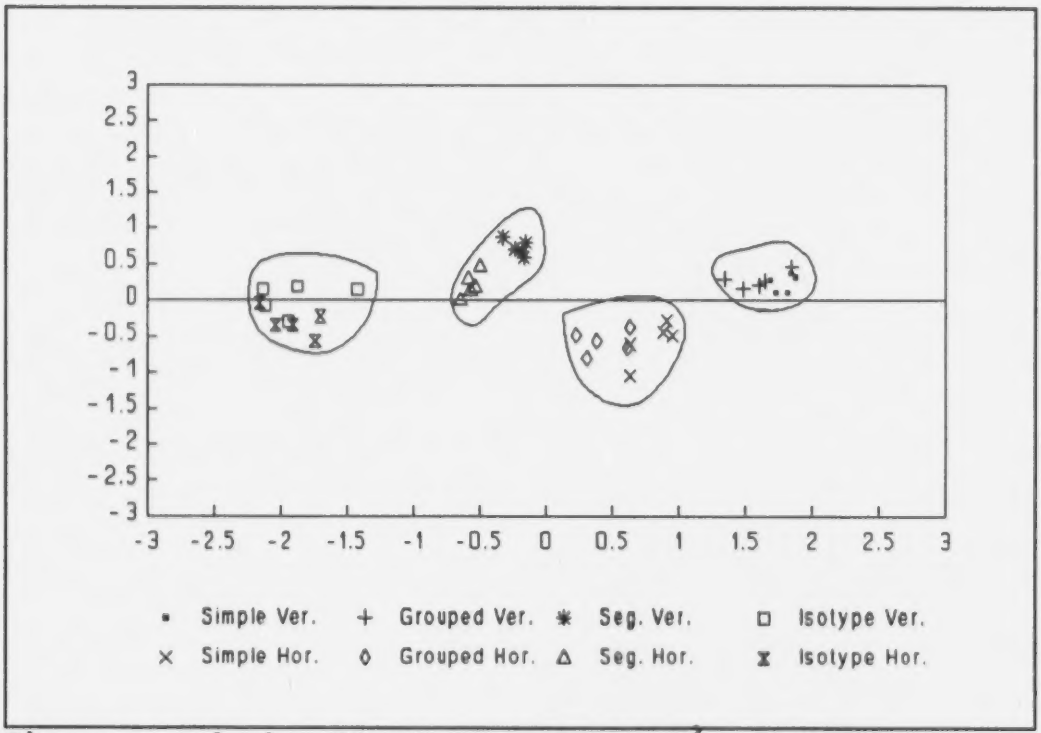


Figure 4: Calculus II. Stress = 0.085. R^2 = 0.973.

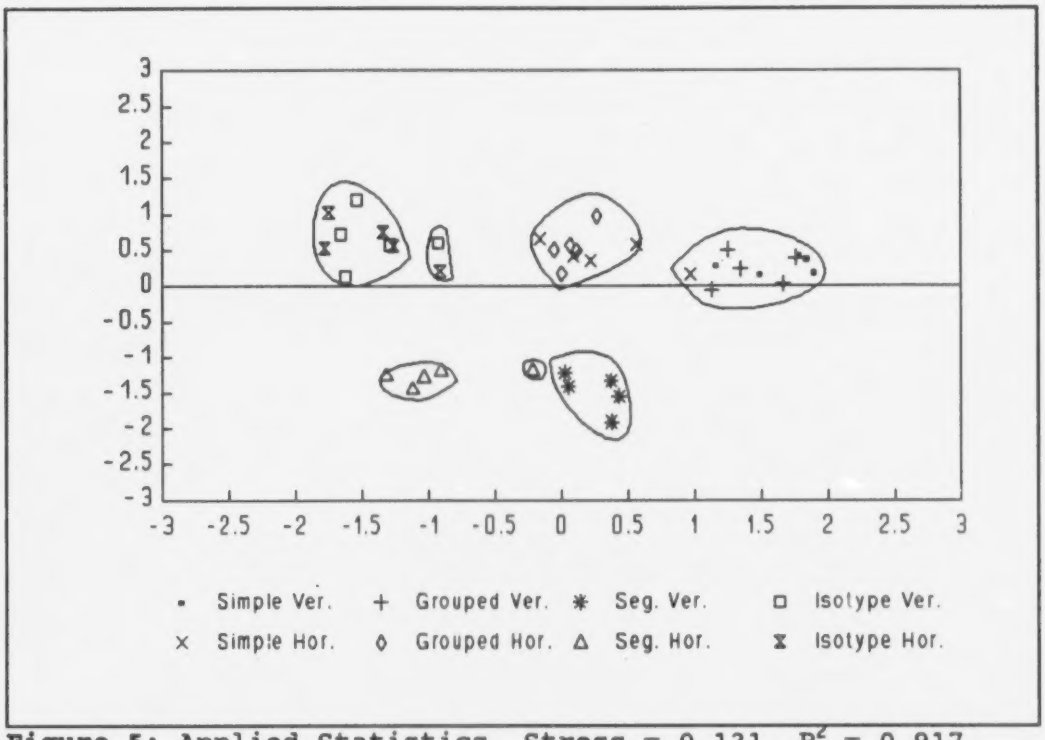


Figure 5: Applied Statistics. Stress = 0.131. R^2 = 0.917.

Table I: Means for the four types of graphs and both orientations for the value reading data.

	Value Reading	
Graph Type	Vertical	Horizontal
Simple	2.88 (0.32)	2.93 (0.32)
Isotype	2.49 (0.67)	2.64 (0.86)
Grouped	2.80 (0.45)	2.86 (0.86)
Segmented	1.83 (0.90)	1.96 (0.87)

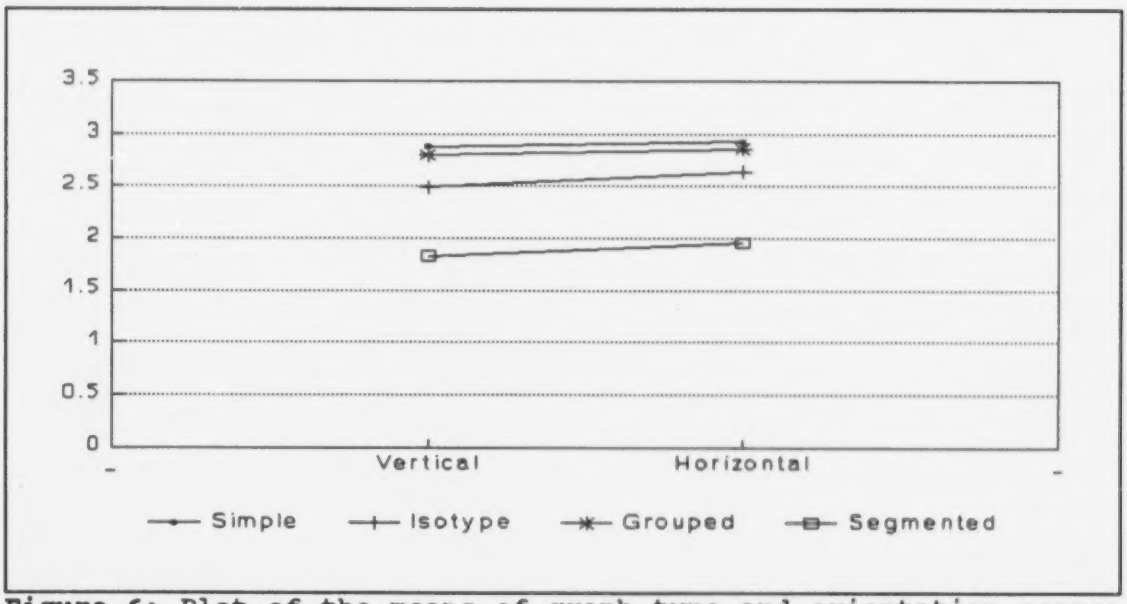


Figure 6: Plot of the means of graph type and orientation scores for the value reading data.

Table II: Means for pattern description data for graph type and orientation. Standard deviations in parenthesis.

	Pattern Description	
Graph Type	Vertical	Horizontal
Simple	2.55 (0.65)	2.63 (0.62)
Isotype	2.36 (0.70)	2.41 (0.64)
Grouped	2.55 (0.73)	2.19 (0.88)
Segmented	1.92 (0.87)	2.04 (0.92)

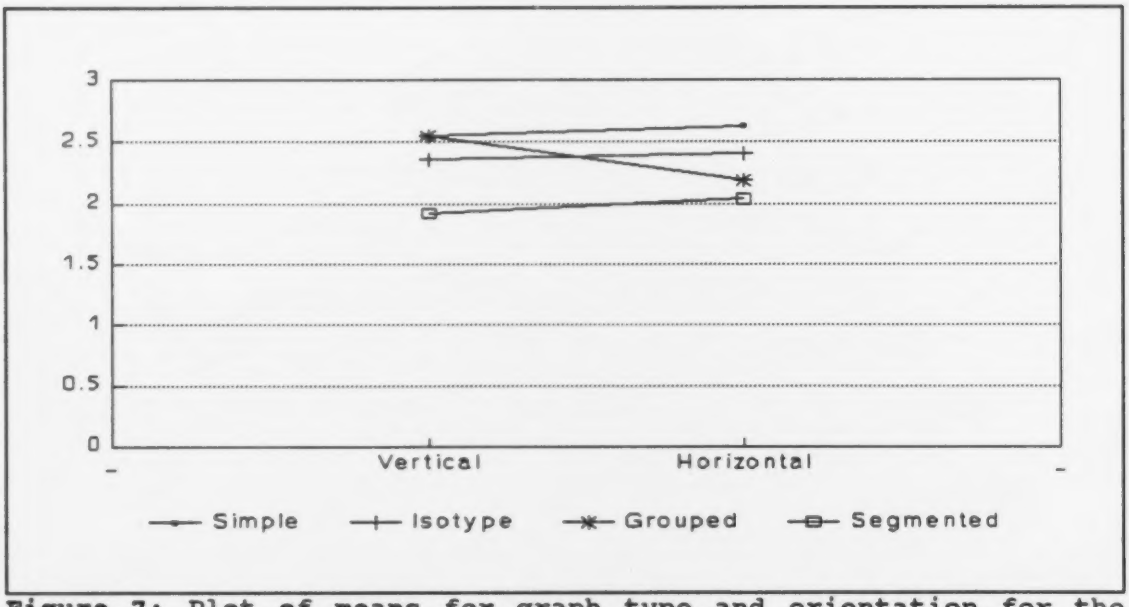


Figure 7: Plot of means for graph type and orientation for the pattern description data.